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Factors Determining the Effectiveness of a Wind Turbine Generator Lightning Protection System

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***Abstract*—As a result of the growing supply and demand for wind power, wind turbine generators are increasingly being installed at sub-optimal sites that have high soil resistivity and high incidence of lightning strikes. This means that lightning protection systems for wind turbines are becoming a critical component of wind farm design. Not only do effective lightning protection systems ensure the safety of the physical wind turbine structure and human operators, they also protect the electrical and control systems installed inside wind turbine generators and safeguard the lives of human operators. This work presents a framework to assess the effectiveness of wind turbine lightning protection systems at the wind farm design phase. Performing the analysis at this early stage reduces lightning-induced downtime, which leads to increased energy yield. Our results show that the grounding system plays a critical role in the wind turbine lightning protection system. For this reason we also analyse various influential parameters of a grounding system design. We present results from full-wave electromagnetic simulations of the complete wind turbine grounding system, including the foundation.**

***Index Terms*—Wind turbine generator, lightning protection system, grounding system**

I. Introduction

THE demand for energy generation from wind farms has increased in recent years [1]. This increase has led to the installation of more wind turbine generators (WTGs) at places with a high probability of lightning strike incidents and high soil resistivity areas [2], [3]. To ensure the growth of wind energy, an effective lightning protection system (LPS) is necessary [4].

Lightning strikes can damage not just the individual wind turbine and its components, but also sections of a wind farm and parts of the grid [5]. This might lead to an increased downtime of WTGs. The increased downtime will not only increase the cost but also the indeterminacy of power generation from WTGs. To reduce lightning-related damages to WTGs, effective design and installation of LPSs [2] and assessment of LPS effectiveness for individual WTG are required.

The WTG LPS aims to dissipate lightning discharge currents safely in the grounding system, diverting them from the electrical and mechanical components in the WTG [6]. The installation of WTGs in a wind farm should consider the probability of lightning incidence and the soil resistivity of the WTG location. In the current practice of wind farm optimization, the lightning protection component is missing. Hence, an assessment of the site for lightning incidence will minimize damage.

The next step is to design an LPS following the international standards [7]. The design of LPSs is based on the evaluation of risk assessment. The IEC 61400-24 standard defines four levels of lightning protection based on the risk assessment. Each lightning protection level (LPL) is associated with a set of design parameters. The parameters of LPL are based on the lightning discharge current parameters which have a critical role in LPSs [8]. A lightning protection system consists of an external LPS, an internal LPS, and the grounding system [9].

The current practice is to design the external LPS, consisting of air termination and down conduction systems, according to the LPL if an individual assessment of the WTG site is possible [7]. Otherwise, a LPS is designed based on the more stringent LPL-1 parameters. The internal LPS is designed to avoid over-voltages and electromagnetic interference due to lightning discharge currents. Finally, the grounding system ensures the proper functioning of all the protection systems.

A WTG grounding system ensures human safety and equipment protection in the event of a power system fault or lightning strike on a WTG [2]. To protect the wind turbine and interconnected electrical equipment, a grounding system that provides a low impedance path to ground is necessary [10].

The effectiveness of a WTG LPS is determined by the individual effectiveness of the LPS components. However, the effectiveness of the external and internal lightning protection systems are determined by the design and installation of the WTG LPS. Therefore the effectiveness of a grounding system is very critical as it ensures the effectiveness of other components of an LPS. The aim of a grounding system according to the IEC 61400-24 [7] standard is to achieve a resistance of less than 10 Ω at low frequencies. However, this doesn't consider the grounding system behaviour at higher frequencies which represent the fast transients of the lightning discharge currents. Moreover, the evaluation of potential distribution is important to protect human operators and livestock from step and touch voltages.

This work presents a framework to evaluate the effectiveness of a lightning protection system for wind turbine generators. The methodology used is according to relevant IEC standards. The effectiveness of the lightning protection system is evaluated by considering all of the individual efficiencies of an LPS. Several case studies are assessed by performing full-

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wave electromagnetic simulations using the CDEGS software package [11]. This work complements a more detailed analysis of various electrode configurations for uniform soil resistivity, presented in [12].

II. Assessment framework for WTG lightning protection systems

This section introduces an assessment framework for WTG lightning protection systems. The factors determining the effectiveness of a WTG LPS are depicted in Fig. 1.

The effectiveness, E_{LPS}, of a WTG lightning protection system consists of several individual components and can be defined as:

$$E_{LPS} = f(E_X, E_I, E_G) \tag{1}$$

where E_X is the effectiveness of the external lightning protection system, E_I is the effectiveness of the internal lightning protection system and E_G is the effectiveness of the grounding system.

A. *Effectiveness of external lightning protection system*

The protection of a WTG from a direct lightning strike is achieved by the external lightning protection system, consisting of an air-termination system and a down conduction system. The effectiveness of an external lightning protection system is a function of the effectiveness of the air termination system E_A and the effectiveness of the down conduction system E_D:

$$E_X = f(E_A, E_D) \tag{2}$$

1) Effectiveness of air-termination system: The purpose of an air-termination system is to protect the WTGs from direct lightning strikes [9]. As the lightning strikes are uncontrolled, an effective air-termination system is required to safeguard the WTG. The effectiveness of an air-termination system has two parts: the sizing effectiveness E_{SA} and interception effectiveness E_{IC}. The effectiveness of an air-termination system can be calculated as:

$$E_A = E_{IC} \cdot E_{SA} \tag{3}$$

2) Effectiveness of down conduction system: The down conduction system provides an electrically conductive path between the air-termination system and the grounding system. The purpose of a down conduction system is to discharge the lightning currents to the grounding system safely, which is achieved by providing multiple parallel conductive paths to the ground. The effectiveness of a down conduction system is determined by E_{SD}, the sizing effectiveness of the down conduction system:

$$E_D = f(E_{SD}) \tag{4}$$

B. *Effectiveness of internal lightning protection system*

The internal lightning protection system of a WTG consists of equipotential bonding, spatial shielding and separation distance, cable routing and cable shielding and the installation of coordinated surge protection devices (SPDs). The effectiveness of an internal lightning protection system is calculated by:

$$E_I = f(E_{EB}, E_{SPD}) \tag{5}$$

where E_{EB} is the effectiveness of the equipotential bonding system and E_{SPD} is the effectiveness of the surge protection.

C. *Effectiveness of grounding system*

The function of the grounding system is to dissipate the lightning discharge currents into the ground without dangerous potential values [13]. An effective grounding system will ensure proper function of an LPS, protecting persons and animals [14]. The influencing factors determining the ground potential rise and impedance are soil resistivity [15], grounding electrodes and lightning discharge current parameters [16]. The effectiveness of a grounding system is calculated as:

$$E_G = f(R_G, A, GPR) \tag{6}$$

where R_G is the resistance of the WTG grounding system at low frequency, A is the impulse coefficient and GPR is the ground potential rise.

The design principles described in IEC 61400-24 [7] are based on IEC 62305-3 [17], which was initially designed for general structures consisting of houses and buildings [18]. The foundations of buildings are typically larger than WTG foundations, allowing long ring electrodes [19].

The main requirement of the grounding system according to IEC 61400-24 [7] is to achieve a resistance value of less than 10 Ω at low frequencies before connecting the grounding system to the rest of the wind farm. This job is challenging at wind turbine sites with high soil resistivity.

The grounding systems designed for power frequencies have a task of achieving low resistance values at steady state or low-frequency analysis [20]. The low-frequency performance assures the effectiveness of the grounding system at the wave trail of the lightning discharge current waveform [8]. However, the high-frequency components are present during the fast rise times of the lightning discharge current. The effectiveness of the grounding system for transients can be evaluated by the impulse coefficient (A), given by [21]:

$$A = \frac{Z}{R} \tag{7}$$

where Z is the impedance of the grounding system at high frequencies and R is the resistance of the grounding system at low frequencies.

The other significant parameter to assess the effectiveness of the grounding system is to evaluate the ground potential rise with reference to a remote earth [22]. This parameter also represents the grounding system behaviour for transients, which helps in avoiding danger to humans and animals.

III. Case Study and Simulation Results

This case study presents an evaluation of the effectiveness of individual components of an LPS. The effectiveness calculations of air-termination and down conduction system are based on the lightning protection level of IEC 61400-24.

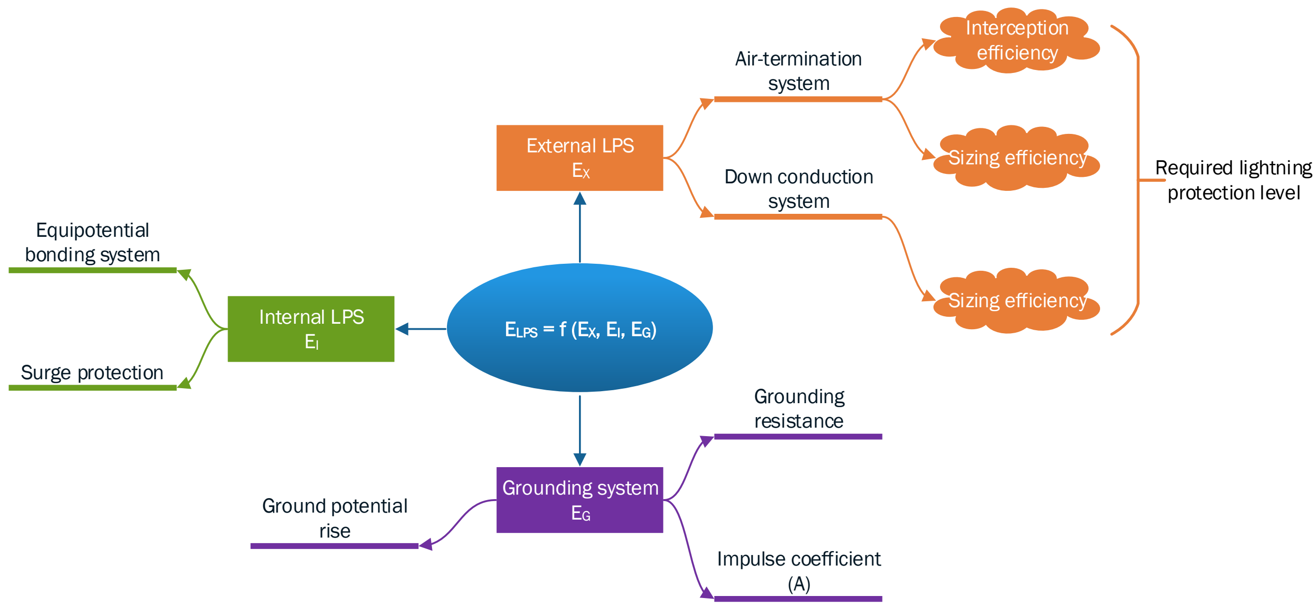

Fig. 1. Factors determining the effectiveness of a WTG LPS.

The effectiveness of the internal LPS is dependent on the individual WTG installations. However, the effectiveness of the grounding system varies significantly depending on the LPL, soil resistivity value, modelling of soil structure, type of grounding electrodes, length of the grounding electrodes, modelling of the grounding system, and frequency, temperature and moisture dependency of soil resistivity.

For an air-termination system designed according to the IEC 61400-24 [7] and IEC 62305-3 [17] standards, the effectiveness for different lightning protection levels is calculated as depicted in Table I [23]. The current practice in the industry is not to perform the risk assessment for individual WTG sites and hence to design a level-1 LPS, which results in the effectiveness of 0.98, as provided in Table I.

TABLE I: Effectiveness of air-termination system

Lightning protection level (LPL)	I	II	III	IV
Sizing effectiveness	0.99	0.98	0.95	0.95
Interception effectiveness	0.99	0.97	0.91	0.84
Total effectiveness	0.98	0.95	0.86	0.8

Similarly, for the down conduction system designed according to IEC 61400-24 [7] and IEC 62305-3 [17] standards, the effectiveness for different lightning protection levels is shown in Table II.

TABLE II: Effectiveness of down conduction system

Lightning protection level (LPL)	I	II	III	IV
Sizing effectiveness	0.99	0.98	0.95	0.95

The effectiveness of the internal LPS mainly depends on the equipotential bonding system and the coordinated surge protection devices. The effectiveness of the equipotential bonding system is evaluated by measuring the resistance between all the conductive parts and the equipotential bus bar. The recommended resistance value is less than 1 Ω [24]. However, resistance of the order of mΩ is preferable. Whether it is a lightning transient or power system fault current, the overvoltages appear at the terminals of the electrical, electronic and control systems installed in the WTGs. The proper installation of coordinated SPDs according to the lightning protection zones [7] and voltage levels will protect the end equipment.

The idea to consider the assessment of LPS is to reduce the downtime and hence increase the energy yield of a WTG. Wind farm designers, in the current practice, don't consider this factor while optimizing the wind turbines in a wind farm. However, factors that can be controllable by wind farm designers are the installation of WTGs at low lightning incidence location and the design of a sound grounding system. An important element of the WTG LPS that ensures the effectiveness of all other components is the grounding system, which depends on the design and installation of the system. Achieving a better grounding system, consisting of a low soil resistivity site, better soil structure modeling and better electrode arrangement and dimensions, improves the effectiveness of the overall LPS. Hence, the effectiveness of a grounding system is analysed in detail for several scenarios. The simulations for this analysis were performed in the frequency domain using the CDEGS software package [11].

The perspective view of the WTG grounding system model used for the simulations is shown in Fig. 2. The grounding system evaluation parameters for this analysis are low-frequency resistance, impulse coefficient, peak potential magnitude, and the step voltages. The permissible limits for step voltages cannot be compared against the standard as there is no fault clearance time [25] associated with lightning discharge currents. The grounding system designs for different soil resistivity values, soil stratification models, electrode configuration

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and frequency dependent soil parameters are analysed in this work.

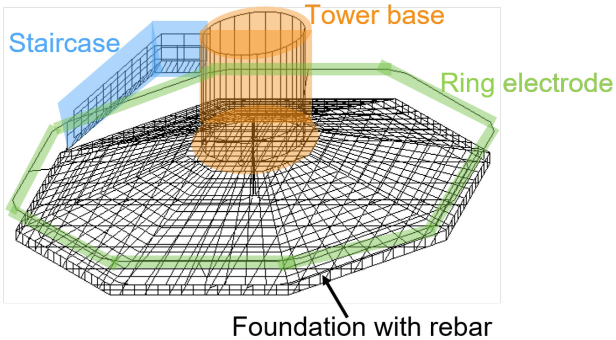

Fig. 2. Perspective view of the WTG foundation (not to scale).

In the first scenario, the grounding system designs for various lightning protection levels according to IEC 61400-24 are compared. The low-frequency resistance of the WTG grounding system increases with increase in soil resistivity as shown in Fig. 3. It can be observed that the low-frequency resistance is constant up to 500 Ωm soil resistivity for all LPLs. This is due to the same length of earth electrode required up to 500 Ωm soil resistivity. However, the resistance increases from 1000 Ωm due to the change in electrode lengths for various LPLs. For 3000 Ωm soil resistivity, the resistance of a LPL-3 designed WTG grounding system is twice that of a grounding system designed to LPL-1.

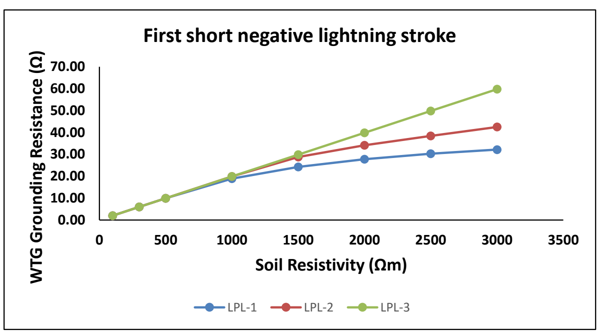

Fig. 3. WTG grounding resistance for different lightning protection levels.

The impulse coefficient is high up to a value of 10 for low soil resistivity values and drops to less than 2 for soil resistivities beyond 1000 Ωm, as depicted in Fig. 4. The high impulse coefficients at low soil resistivity are due to the high impedance values at higher frequencies and relatively small resistance values at low frequencies. The impulse coefficient value of 1 represents a resistive behaviour, less than 1 represents capacitive behaviour, and greater than 1 represents inductive behaviour of the grounding system. The higher impulse coefficient at low soil resistivity values indicates the inductive response of the grounding system at high frequencies. However, the low values of impulse coefficient at higher soil resistivity values indicate the poor behaviour of the grounding system at the low frequencies.

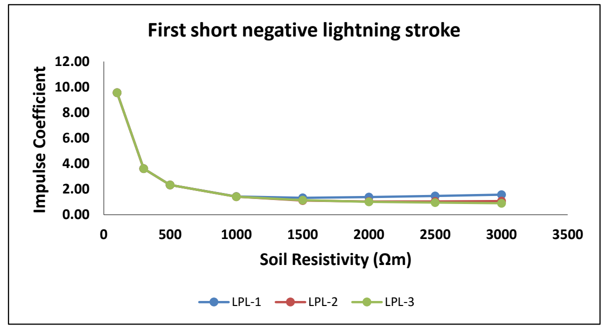

Fig. 4. Impulse coefficient of the WTG grounding system for first short negative lightning discharge current parameters.

The potential distribution around the WTG foundation is observed to be equipotential for all the LPLs at low frequencies, as depicted in Fig. 5. However, at higher frequencies, the potential profile experiences a significant change within a small area with high potential spikes, as illustrated in Fig. 6. The peaks are due to greater current dissipation at the impulse injection points and the connection point of the staircase to the WTG grounding grid.

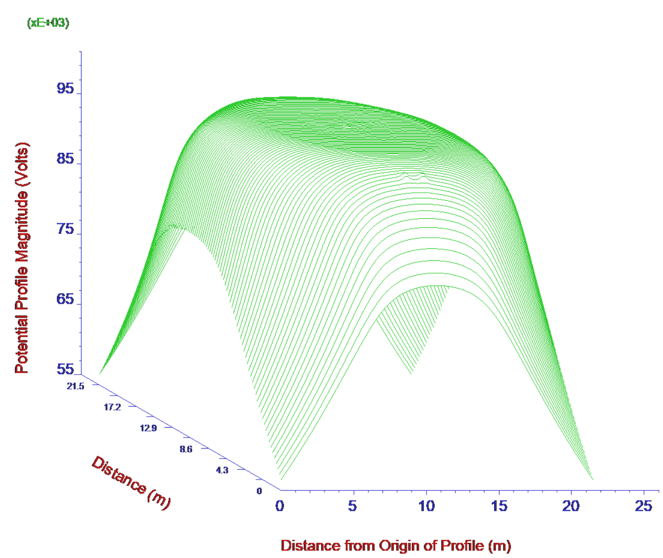

Fig. 5. Potential distribution of the WTG grounding system at 5 kHz for soil resistivity of 100 Ωm, LPL-1.

It is critical to evaluate the peak potential magnitude and the step voltages at the WTG grounding system and the area surrounding the WTG foundation. As depicted in Fig. 7, the peak potential magnitude increases with increase in soil resistivity for all LPLs. Interestingly, the peak potential for the grounding system designed for LPL-1 is higher than LPL-2 and LPL-3. Although a unit current injected into the WTG grounding system results in lower potential magnitude for LPL-2 and LPL-3 compared to LPL-1, it is the high peak current magnitude of LPL-1 that results in higher potential magnitudes. However, the potential values at higher frequencies are much more significant than low-frequency magnitudes not only due to high lightning discharge current magnitudes but also due

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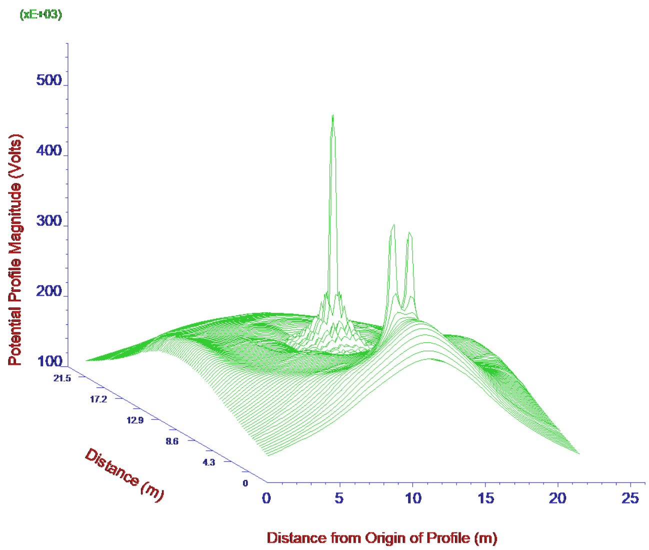

Fig. 6. Potential distribution of the WTG grounding system at 1 MHz for soil resistivity of 100 Ωm, LPL-1.

to high-frequency inductive components. The predominant factor responsible for high potential profiles is high-frequency components of the lightning discharge current [26].

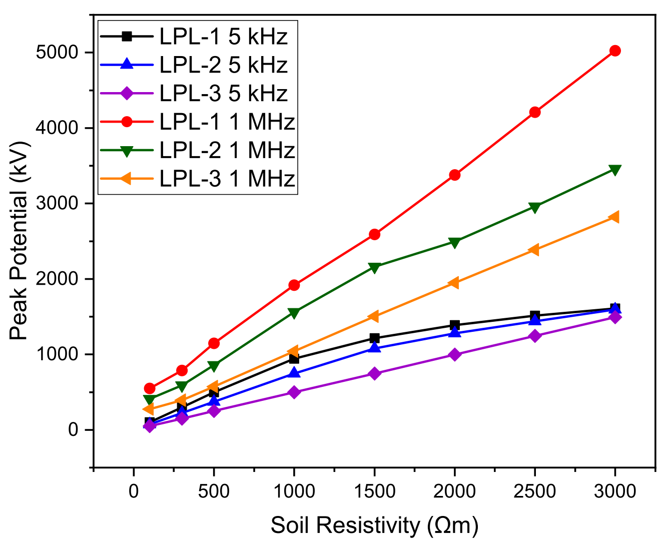

Fig. 7. Peak potential magnitude at various lightning protection levels.

Now, the maximum possible step voltages are evaluated for all the LPLs, as depicted in Fig. 8. The low step voltages at low-frequency are due to the equal distribution of electric field and current density throughout the WTG grounding grid. It is important to observe that lower step voltages are noted for high soil resistivity values due to longer electrodes making an equal potential distribution. However, at high frequencies, the current density and electric field are mostly concentrated at the current injection point. Moreover, the current density is higher for WTG earth electrodes compared to the rebar. Hence, larger step voltages are observed at high frequencies.

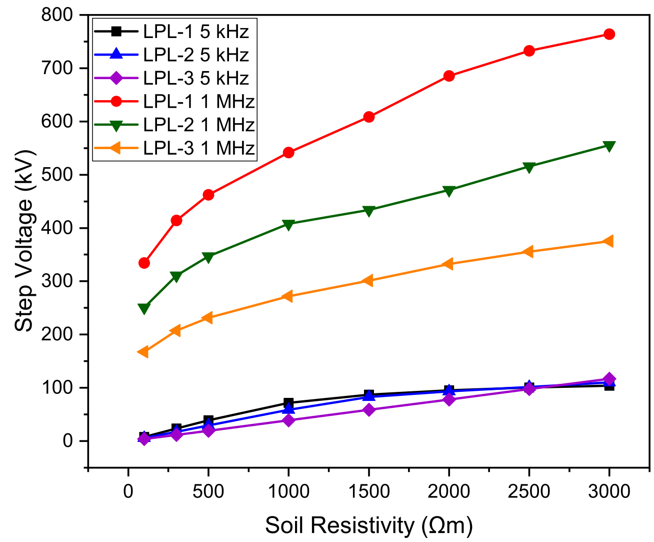

Fig. 8. Step voltage for various lightning protection levels.

It is interesting to note the behaviour of a WTG grounding system designed to LPL-2 or LPL-3 and subjected to a lightning discharge current that would normally only be experienced by a LPL-1 system. The low-frequency resistance of the LPL-2 WTG grounding system is 42.5 Ω compared to 32.2 Ω for the LPL-1 grounding system at a soil resistivity of 3000 Ωm. Moreover, the low-frequency resistance further increases to 59.8 Ω for LPL-3. The high-frequency impedance has no change for all the LPLs, due to the negligible effect of electrode length at higher frequencies. However, the impulse coefficient is higher for LPL-1 compared to LPL-2 and 3. This impaired performance is due to the compromise of low-frequency effectiveness of the grounding system. Further, the grounding system designed for LPL-2 and struck by LPL-1 lightning experiences a peak potential of 2125.55 kV against 1594 kV for LPL-2 lightning at 5 kHz. At 1 MHz, the potential magnitudes are 4611.77 kV and 3458.81 kV. The increase in the potential for an LPL-3 design experiencing an LPL-1 stroke is higher than that of LPL-2. At 5 kHz, the potentials are 2988.63 kV for an LPL-1 stroke compared to 1494.31 kV for an LPL-3 stroke. At 1 MHz, the potential magnitudes are 2820.13 kV and 640.29 kV, respectively.

In the second scenario, the analysis of grounding systems for various electrode configurations is performed. The electrode configurations are: ring, horizontal, vertical, ring-horizontal and ring-vertical. For high soil resistivity sites, the grounding system with a ring electrode configuration is not feasible due to the requirement of multiple ring electrodes, which must be installed with sufficient separation so as not to interfere (electric fields) with each other The ring electrodes should be installed in a way that should not interfere with the electric fields of the ring electrodes. As illustrated in Fig. 9, the low-frequency resistance is lowest for the grounding system with horizontal electrodes. The next best electrode configuration is the ring-horizontal electrode. Besides, the low-frequency resistance is further reduced with increase in the length of the horizontal electrode, as observed for a combination of ring and 120 m horizontal electrode for 2000 Ωm soil resistivity. The low-frequency resistance of high soil resistivity sites is very high. This is mainly due to the increased resistivity and lack of electrode lengths to dissipate the lightning discharge currents.

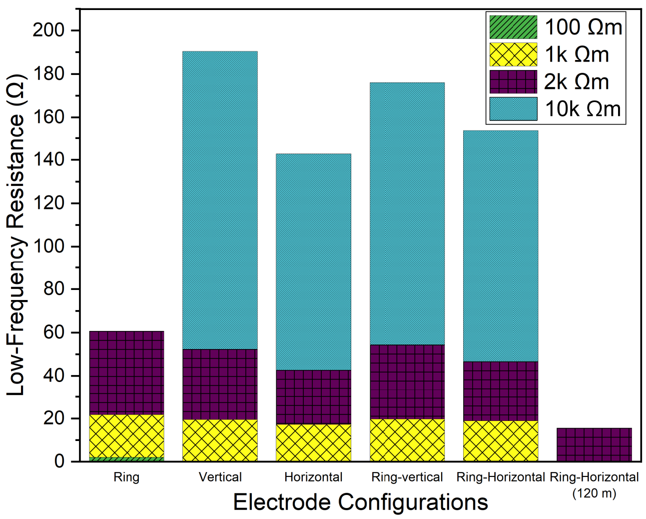

Fig. 9. Comparison of low frequency resistance for various electrode configurations for uniform soil resistivities.

However, the impulse efficiency of the grounding system is different from that of the low-frequency performance. As depicted in Fig. 10, the impulse coefficient at 100 Ωm is very high compared to higher soil resistivity sites. This is due to the high impedance of the grounding system at higher frequencies and small values of low-frequency resistance. At higher soil resistivities, the ring electrode and its combination with other electrodes has better impulse coefficients due to the better performance of ring electrodes at high frequencies. The performance degradation of the horizontal electrode configuration is mainly due to its better performance at lower frequencies.

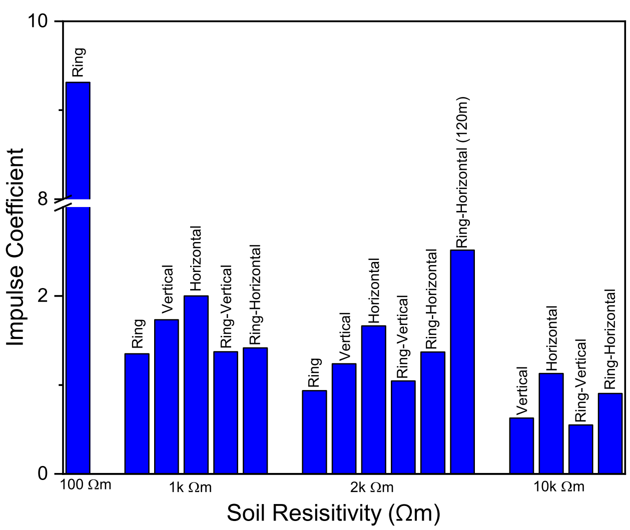

Fig. 10. Comparison of impulse coefficient for various electrode configurations for uniform soil resistivities.

In the final scenario, the effectiveness of the WTG grounding system for various soil models for different electrode configurations is compared. A set of measured soil resistivity values were modeled as various soil structures, viz. uniform, horizontal two-layer, and horizontal three-layer soil structures [27]. As shown in Fig. 11, the low-frequency resistance is lowest for horizontal earth electrodes irrespective of soil structure. Also, it is noted that the horizontal three-layer soil model has the lowest low-frequency resistance amongst all the soil models.

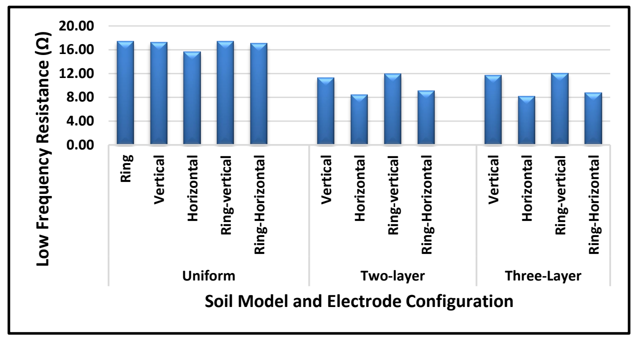

Fig. 11. Comparison of low-frequency resistance for various electrode configurations with various soil models

As illustrated in Fig. 12, the impulse coefficient is best for the electrode configuration consisting of a ring electrode. This is due to the better performance of the ring electrodes at high frequencies. The impulse coefficients are better for the uniform soil model compared to horizontal two & three layer soil structures. This is due to the performance impairment of the uniform soil model at low frequencies.

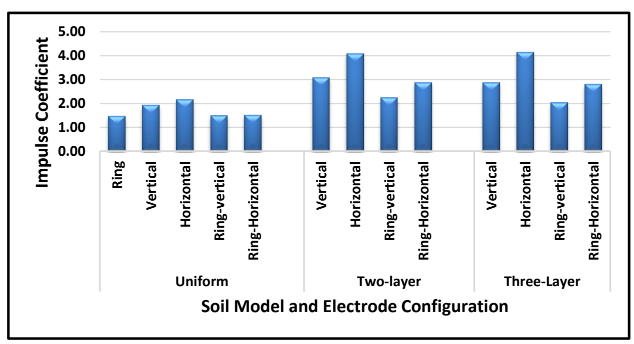

Fig. 12. Comparison of impulse coefficient for various electrode configurations with various soil models and frequency dependent soil parameters.

The potential gradient developed due to the lightning impulse current is minimised for horizontal electrodes for all the soil models at low-frequencies. Moreover, the potential is lowest for the horizontal three-layer soil model amongst all the soil structures. The high-frequency potential magnitude is minimised for the ring-horizontal electrode configuration, as depicted in Fig. 13.

The step voltages have a minimum value for horizontal electrodes at low frequencies irrespective of the soil model.

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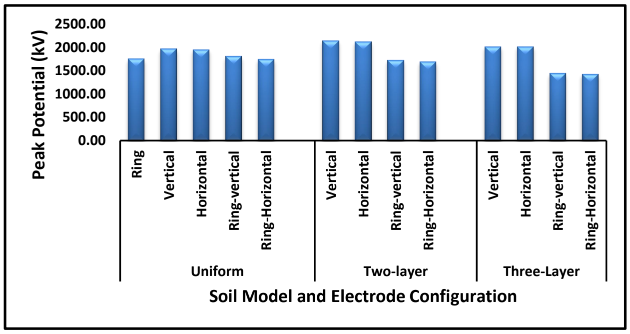

Fig. 13. Peak potenial for various electrode configurations and soil models.

Also, a minimum amount of step voltage is observed for a horizontal three-layer soil structure at low frequencies. However, at high frequencies, the ring-horizontal electrodes offers the lowest step voltage, as illustrated in Fig. 14.

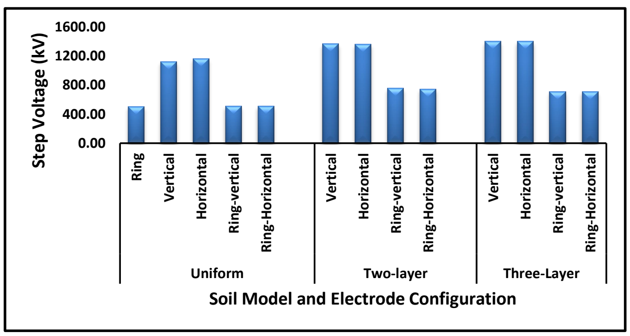

Fig. 14. Step voltage for various electrode configurations and soil models.

The horizontal electrode configuration provides a low resistance grounding system at low-frequencies due to the uniform electric field distribution leading to an equipotential surface throughout the grounding grid. At higher frequencies, the current dissipation is higher at the impulse injection point. Moreover, the potential rise at the ring electrodes is higher compared to other electrodes. A similar phenomenon is observed for various soil structures and LPLs. Hence, a ring electrode in combination with a horizontal electrode can be a better electrode configuration for all the soil structures and LPLs. Besides, the frequency dependent soil parameters pose low soil resistivity values at higher frequencies and permittivity values.

The effectiveness of a WTG lightning protection system depends mainly on two factors: firstly, on the WTG site and secondly on a well-designed grounding system. The assessment of a WTG site for lightning probability and low soil resistivity is vital in the wind farm optimization for energy yield and safety. The WTG grounding system designed with an accurate soil resistivity measurement and soil modeling along with an electrode configuration of the ring and horizontal electrodes ensures an effective grounding system. The increase in the length of horizontal electrodes beyond an effective length does not affect the high-frequency impedance. However, they improve the low-frequency resistance which is also the steady state impedance of the grounding system.

IV. Conclusion

This work presented a procedure for assessing the effectiveness of WTG lightning protection systems. The installation of WTGs at sites with low probability of lightning incidence and the design of effective grounding systems are the parameters controllable by the wind farm designers. This work explains that the effectiveness of the grounding system can be improved by proper design of earth electrodes, soil stratification, and low resistivity soil sites. Following are the main contributions of this work:

1) This work provides a framework to evaluate the effectiveness of WTG LPSs.
2) The impulse coefficient is not the only parameter to assess the effectiveness of a LPS. The low-frequency resistance and the potential distribution should also be considered.
3) The electrode configuration with ring and horizontal electrodes is the most effective for a WTG LPS.
4) Accurate soil stratification is important for an effective LPS.
5) The design of the WTG grounding system for LPL-1 parameters is recommended.

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